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Secondary settlements of 4 Danish road embankments on soft soils

Tassements secondaires de 4 remblais routiers danois sur argile molle

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SYNOPSIS 4 road embankments in Denmark placed on compressible postglacial deposits have been followed very closely from the start of the construction. The observation method has allowed continued observations to be carried out without any breaks. In 3 cases the observation period has been about 10 years - long enough to give some information about the longterm behaviour. Two embankments represent a final state of normal consolidation. In these cases the observed rates of secondary compression were found in fine accordance with oedometer values from normally consolidated load increments. Two other embankments have confirmed earlier reported effects of overloading. Finally traffic data have been related to the observed results.

INTRODUCTION

In connection with developments of the road system in Denmark during the past 10-20 years the method of preconsolidation instead of exchange of soft compressible layers has occasionally been used.

A summary of the consolidation theories and experiences attached to loadings and unloadings of normally consolidated soils has earlier been given by Veder (1983). Especially is mentioned that the development of secondary settlements strongly depends on the magnitude of overload and on the length of the ballasting period.

Still there may be some uncertainties about the rates of secondary settlements and how to perform laboratory tests in the best way in order to determine relevant properties fit for calculations of the long term settlements.

Concerning road embankments there are furthermore uncertainties about the influence of the traffic, which represents a kind of dynamic loading in addition to the static loading from the fill materials.

In the following 4 examples from 3 different localities in the northern part of Denmark are presented. They may be of some interest because of the lengths of observation periods, which - except in one case - have been around 10 years.

LOCALITIES

The following three localities are regarded: Dybvad, Klarup, and Vegger. Fig. 1 indicates their positions on a map of the northern part of Jutland in Denmark.

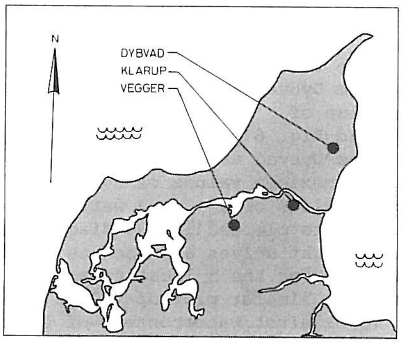

Figure 1. Northern part of Jutland. Localization of embankments.

DYBVAD (Case 1)

The main results of soil explorations and settlements are shown in Fig. 2.

The compressible layers consist of peaty and sandy organic clays sedimented in a younger local moor (fresh water).

The embankment was built up in small layers of sandfill, placed directly on the ground surface. The excess porepressures in the soft soils were followed by means of piezometers placed ahead, and the stability problems were solved by utilization of the increase of strength, which followed the compression step by step. Thus the next layer was delayed until low levels of excess porepressures were obtained. Having the advantage of a relative high permeability the full height of fill was reached successfully in 7 months.

In this case non unloading has taken place, and the embankment in Dybvad therefore with certainty represents a normally consolidated state.

A time-settlement curve for the final applied pressure (Fig. 3) has the same form as the time-settlement curve from a similar loading step in the oedometer. The curves are plotted in a combined $\sqrt{t}$-log(t) diagram as proposed by Brinch Hansen (1961).

The time curve indicates the quantities of Table 1. The maximum settlements of primary consolidations are found in good accordance with the result of a simple conventional calculation based on an average value of

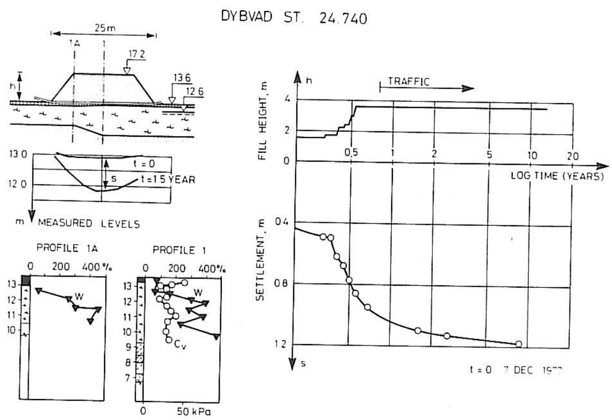

Figure 2. Data and observed settlements in Dybvad.

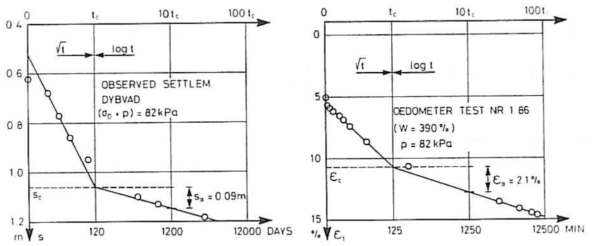

Figure 3. Time-settlement curves. Field and laboratory.

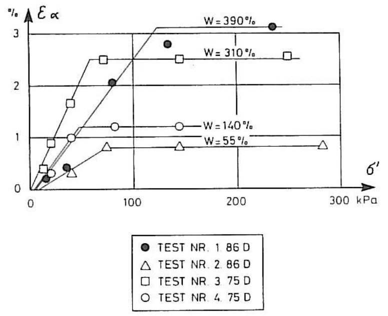

Figure 4. Coefficients of secondary compression in oedometer tests from Dybvad.

Table 1. Observed quantities from Dybvad.

H	σ_o'	p	$s_{(c+i),\max}$	t_c	$\varepsilon\alpha = \frac{C_\alpha}{1+e_o}$	H_D
m	kPa	kPa	m	days	%	m
4.2	14	68	1.06	120	2.1	1.8

consolidation index $Q = C_c/1+e_o$ obtained from a number of oedometer tests.

Also the value of t_c ($\sim T = \pi/4$) is in accordance with the laboratory results if the average length of drainage path H_D is 1.8 m which is not unlikely.

The value of $\varepsilon\alpha$ has been compared with the following test results.

OEDOMETER TESTS

Oedometer tests have been carried out on undisturbed samples from the 3 localities. The samples were recorded in 70 mm tubes of plastic or steel. The size of the specimens were D x H = 70 x 35 mm or 60 x 30 mm. The oedometer used was of the new Danish type developed and described by Jacobsen (1970).

Most of the tests were performed against determination of the proporties Q, c_v, and σ_{pc}. The loading procedure ($\Delta p = p$) was followed until a straight curve was obtained in a $\log(\sigma')-\varepsilon_c$ diagram. The time curve referring to every load increment was followed until a straight curve of secondary compression in a $\log(t)-\varepsilon_1$ diagram was obtained.

It seems like the values of $\varepsilon\alpha = \Delta\varepsilon_1/\Delta\log(t)$ in most of the tests become nearly constant, when the specimen has reached a state of normal consolidation. For the load increaments ahead, in which this state is not yet obtained, the values of $\varepsilon\alpha$ are smaller.

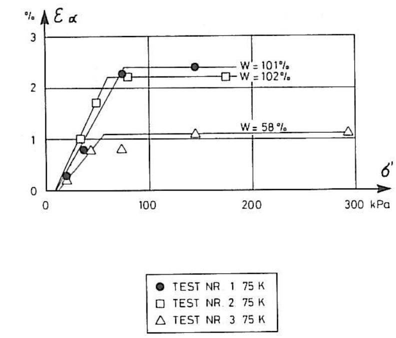

Figure 5. Coefficients of secondary compression in oedometer tests from Klarup.

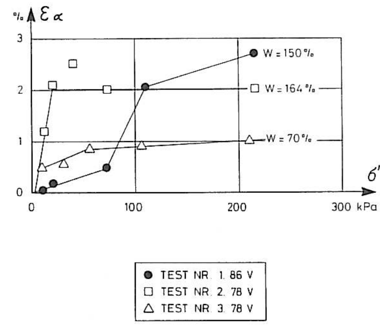

Figure 6. Coefficients of secondary compression in oedometer tests from Vegger.

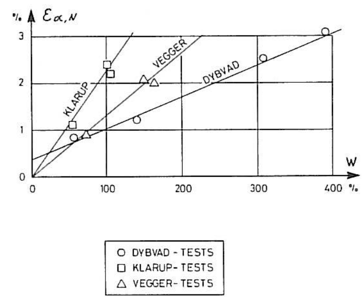

Figure 7. Normal consolidated values of $\varepsilon\alpha$ as function of w. (Secondary consolidation)

In Fig. 4 the values of $\varepsilon\alpha$ from 4 oedometer tests on samples from Dybvad are plotted against the corresponding value of $\sigma' = p$.

In Fig. 5 and Fig. 6 similar results on samples from Klarup and Dybvad are plotted.

The constant maximum values of $\varepsilon\alpha$ are indicated $\varepsilon_{\alpha,N}$. Corresponding values of $\varepsilon_{\alpha,N}$ and watercontent of the sample (w) are plotted in the diagram on Fig. 7. Individual straight curves are used as simple approximated functions for the 3 localities.

Fig. 8 shows a similar plot of values of consolidation index (Q) against watercontent of the sample (w). Also in this case individual straight lines are used as suitable approximations.

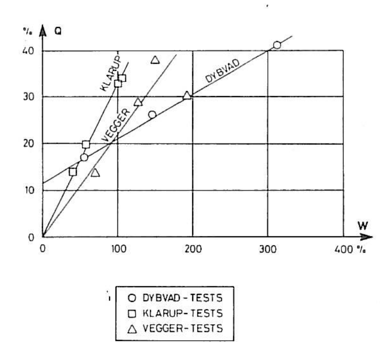

Figure 8. Consolidation index Q as function of w. (Primary consolidation)

ESTIMATION OF SECONDARY SETTLEMENTS

It is natural to believe that the coefficients of secondary compression measured in normally consolidated states are relevant values for estimating the long term settlements of an embankment on normally consolidated deposits, which have not been unloaded.

In Dybvad the watercontent of the soft soils is varying strongly. (Fig. 2, profile 1.) Values between 60% and 475% are measured. The best mean value taking layer thicknesses into account is w_m = 276%.

The straight curve representing the test results from Dybvad in Fig. 7 is used. The function can be expressed:

$$\varepsilon_{\alpha,N}\ (\%) = 0.35 + 0.0065 \cdot w\ (\%)$$

If w_m = 276% is inserted the estimated value will be $\varepsilon_{\alpha,N}$ = 2.1%.

The field value is determined as $\varepsilon_{\alpha,F} = \Delta s_\alpha/H$ = 0.09 m/4.2 m = 2.1%.

The close agreement is found interesting and taken as an indication of a very little influence from the traffic loads.

KLARUP (case 2 + 3)

Two sections of the same road are regarded. The main data from investigations and observations are shown in Fig. 9 and in Fig. 10. The compressible soils consist of organic marine deposits, which have been raised above sea-level since the Stone Age. The deposits are normally or slightly overconsolidated.

In both cases an overload has been used.

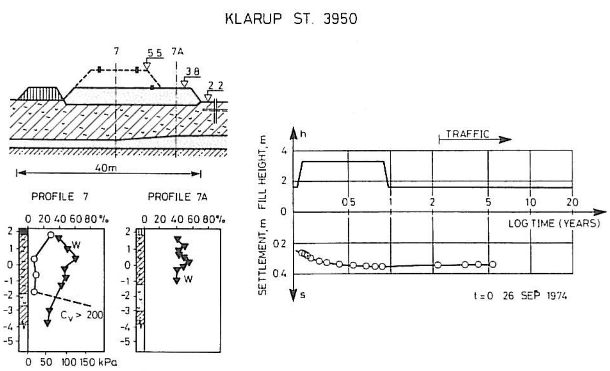

Figure 9. Data and observed settlements in Klarup. ST. 3950.

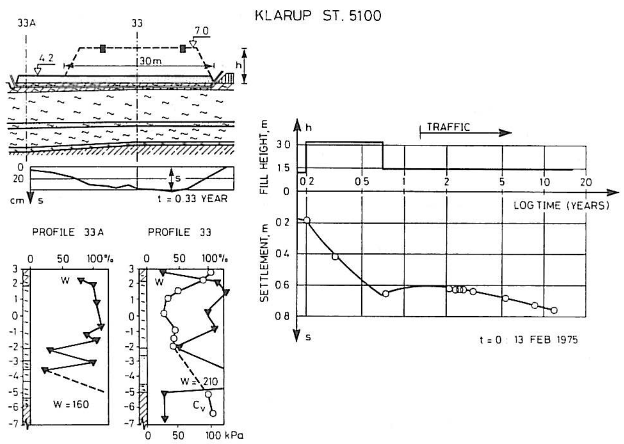

Figure 10. Data and observed settlements in Klarup. ST. 5100.

In ST. 3950 the primary compression was already finished when the overload was placed. This means that the state after unloading really was overconsolidated. This section has only been followed in a period of 4 years after unloading, but in this period the settlements - after a very slightly heave - have only been a few mm.

In ST. 5100 the situation was opposite. The overload was placed shortly after the start, and the planned ballasting period was shortened becuase of a desire of accelerating the finishing works. The settlements had scarcely reached the calculated value of primary compression for the final load when the overload was removed. The final state was probably normally consolidated and not overconsolidated. In Fig. 11 the time-curve after unloading is compared with a time-curve produced in a laboratory test, in which an imitation of the field loadings is attempted. The length of ballasting period in the oedometer was determined by the equation:

$$t_{lab} = t_{field} \cdot H^2_{D,lab}/H^2_{D,field}$$

- but coincident values of consolidation ratio, U, are difficult to obtain.

The time curves have the same shape with a minor primary decompression, which after a while turn to continued secondary settlements. Resulting negative excess pore pressures in the middle of the layers after unloading must explain the heaves.

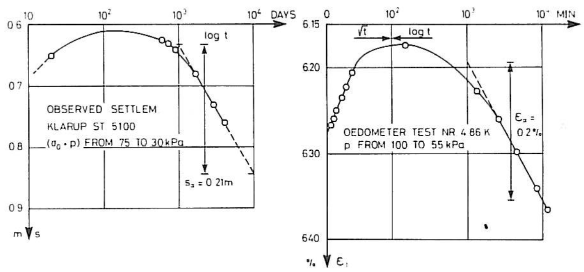

Figure 11. Time-settlement curves after unloading.

The field value of $\varepsilon\alpha$ is 3.0%. The oedometer value from the test described is only 0.2%.

Estimating $\varepsilon\alpha$ in the same way as in the case of Dybvad by using the normally consolidated values $\varepsilon_{\alpha,N}$ from Fig. 7 the result will be $\varepsilon_{\alpha,N}$ = 2.9% ($\varepsilon_{\alpha,N}$ = 0.022·w%, w_m = 130%).

It is seen that the observed rate of secondary compression - similar to the case of Dybvad - is in fine agreement with the oedometer values $\varepsilon_{\alpha,N}$ from normally consolidated loading steps. In this case the overload has apparently not reduced the rate of secondary settlements at all - just delayed these settlements about 1 year. The wrong value of $\varepsilon\alpha$ from the oedometer curve in Fig. 11 must be explained by the fact that the specimen was not brought into a normally consolidated state.

The slight difference between $\varepsilon_{\alpha,N}$ and $\varepsilon_{\alpha,field}$ may indicate a minor influence of traffic.

VEGGER (case 4)

The main facts and data are given in Figure 12. The compressible soils are postglacial deposits similar to the deposits in Klarup.

The embankment was ballasted with an overload of 50 kPa, which was kept until a consolidation ratio U = 60% was obtained. This valuation was based on measurements of pore pressures. The conditions after unloading thus must be considered as overconsolidated.

The heave after unloading is also observed in oedometer tests imitating the loading history as good as possible. These tests have given values of $\varepsilon\alpha$ = 0.3% after unloading. The normally consolidated value corresponding to the mean value w_m = 150% is $\varepsilon_{\alpha,N}$ = 2.0% (Fig. 7). The field value observed is $\varepsilon_{\alpha,field}$ = 0.8%. In this case the rate of secondary settlements have been reduced around 60% in proportion to the rate expected under normally consolidated conditions.

SETTLEMENT OBSERVATIONS

The in-situ settlements have been measured by use of the method described by Bergdahl (1967).

Rubber tubes are placed and covered in tiny ditches across the road-line before start of the filling works. These rubber tubes are levelled by an instrument drawn through the tubes. Thus the settlements are measured on the surface of the compressible soils.

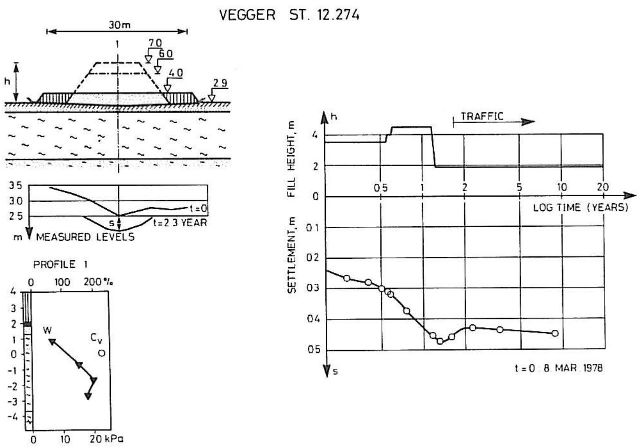

Figure 12. Data and observed settlements in Vegger.

The great advantage of this method is that the measurements take place beside the embankments - undisturbed of construction works and traffic. The settlements can be followed from the very start and the observations can be continued without any breaks in a long period after the road has been taken into use.

TRAFFIC

The influence of traffic on the long term settlements probably depends on the traffic intensity and sort. The final height of embankment may play a role (contributions from compaction of the fill materials are kept outside).

The traffic intensity can be quantified in different numbers based on countings. In Table 2 the actual intensities are compared by mentioning the number of 6 t lorries in the mean day of the year.

Table 2. Summary of data significant to the long term settlements.

Locality	Normal cons.	Over cons.	Unloading	p kPa	Lorr. / day	$\varepsilon_{\alpha,N}$ %	$\varepsilon_{\alpha,obs.}$ %
Dybvad(1)	x			70	100	2.1	2.1
Klarup(2)		x	x	35	300	1.0	∿0
Klarup(3)	x		x	30	300	2.9	3.0
Vegger(4)		x	x	25	150	2.0	0.8

Table 3. Characterizing properties of the compressible soils.

Locality	W_P %	W_L %	I_P %	W_{nat} %	e_o
Dybvad	242	368	126	(70-475)	(1.4 - 6.0)
Klarup	69	122	53	(40-150)	< 3.1 <
Vegger	107	124	17	(60-200)	(1.7 - 4.3)

CONCLUSIONS

4 embankments on normally consolidated compressible soils have been followed in periods up to 11 years from start. These periods have been long enough to obtain some experiences on the long term behaviour under different circumstances.

1. If no unloading takes place the coefficient of secondary compression $\varepsilon\alpha$ can be determined in the oedometer by using loading steps, which have reached a state of normal consolidation.

2. Overconsolidated conditions can be obtained in the field, if the ballasting period is long enough. $\varepsilon\alpha$ is then strongly reduced - at least in a long period. If the state remains normalle consolidated after unloading (ballasting period too short) the settlements will continue after a while with a rate $\varepsilon_\alpha = \varepsilon_{\alpha,N}$.

3. Traffic has been of no influence on a rather high embankment. It may have increased $\varepsilon\alpha$ slightly in the cases of Klarup 5100 and Vegger.

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